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Moisture content estimation of green softwood logs of three species based on measurements of flexural vibration

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Abstract

The moisture contents of sugi (*Cryptomeria japonica*), todomatsu (*Abies sachalinensis*) and hinoki (*Chamaecyparis obtusa*) logs were estimated using a method of moisture content estimation proposed in our previous study. In the course of estimation, it was revealed that the regression line of the correlation between specific dynamic Young's modulus (E/ρ) and tangent loss ($\tan\delta$) of green wood was different from that of moisture-conditioned wood and showed species dependency, both of which are not previously reported. Regression lines at the fiber saturation point (FSP) were constructed for each species by measuring E/ρ and $\tan\delta$ from the flexural vibration of green small specimens and correcting the E/ρ values at their own moisture contents into E/ρ values at the FSP. The correlation of green wood in this study was different from that reported in previous studies of moisture-conditioned wood near the FSP. The correlations of sugi and hinoki were similar, whereas those of sugi and todomatsu were different despite no previous report of species dependency in air-dried wood. The moisture contents 86 logs (not those used to prepare small specimens) were estimated using regression lines of each species. The standard deviation of the difference between the estimated moisture content and the measured moisture content was 15.7%. A systematic error of 25.9% in moisture content was attributed to the different methods of specimen support used for small specimens and logs.

Keywords Moisture content estimation, Tangent loss, Specific dynamic Young's modulus, Green wood, Species dependency

Introduction

It is important to know the moisture content of green wood because it allows fine tuning of the drying schedule and grading by air-dried density before drying. However, it is difficult to non-destructively determine the moisture content with accuracy when the moisture content is well above the fiber saturation point (FSP), as in green wood. For example, moisture content meters that are widely used on site use a measurement principle that is based on the decrease of electrical resistance or the increase of capacitance as related to the increase of moisture content inside the wood. These instruments tend to show low accuracy in high-moisture samples and are likely influenced by wood density. Previous studies of near-infrared spectroscopy [1] showed that moisture content below the FSP can be measured accurately by focusing on indices related only to water content, although large specimens or those with moisture content above the FSP could not be measured with accuracy. Recently, the phase and attenuation of high-frequency electromagnetic waves and gamma rays through timber has been identified as a new index that is highly related to log heartwood moisture content [2]. Although the estimation precision was

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much improved over methods from previous research, this method has some problems related to variations of up to ± 50% and requires specialized equipment.

In addition to measuring moisture content by monitoring the transmission of energy through wood, other methods can be considered based on changes in the mechanical properties of wood according to the moisture content. For example, the specific dynamic Young's modulus (E/ρ) decreases with increasing apparent density when the moisture content is above the FSP. In addition, sound velocity and resonance frequency are known to change with moisture content above the FSP because they depend on E/ρ [3, 4]. Indeed, some previous studies [5–7] have used sound velocity and Aratake et al. [8] have used resonance frequency in attempts to determine moisture content above the FSP. However, while E/ρ depends on wood moisture content, it may also show individual variations caused by the average microfibril angle (MFA) of cellulose [9, 10], meaning that E/ρ may still show variation at the same moisture content. These limitations meant that previous studies that aimed to estimate moisture content using E/ρ needed to introduce an initial value or use statistical processing.

Tangent loss ($\tan\delta$), which is another mechanical property of wood, is already known to have a strong negative correlation with E/ρ in air-dried wood because $\tan\delta$ is also influenced by MFA in the same manner as E/ρ [11–14]. However, in contrast with E/ρ, $\tan\delta$ is constant above the FSP. Therefore, the intercept of the regression line of the correlation between E/ρ and $\tan\delta$ decreases and the slope is constant when the moisture content increases above the FSP.

Using these characteristics, our research group used the intercept of the regression line as a general index of moisture content above the FSP. This work was based on an equation for estimating the moisture content of wood using the regression line of correlation at the FSP between two vibrational properties (E/ρ and $\tan\delta$), which can be obtained from flexural vibration tests of target wood specimens with moisture content above the FSP [15]. To verify the equation, the regression line at the FSP was obtained for 23 sugi green square lumbers, and the moisture contents of the same lumbers during drying were calculated from the equation. As a result, the average measured moisture contents from the oven-dry method were successfully predicted.

However, there were two main issues with our previous study. The first issue was that the regression line of the correlation between E/ρ and $\tan\delta$ obtained from green sugi lumber was significantly different from the regression line near the FSP observed in previous research [16–18] using moisture-conditioned wood. Given the importance of establishing the generality of the regression line of the correlation, which is essential for our proposed method, small specimens similar in size to those used in previous research were used to establish whether the regression line from our previous work was valid. In addition, the species dependency of regression line was also investigated to reveal the generality of the regression line. To our knowledge, there is no report of species dependency for correlation of green wood moisture content, although species dependency is reported for air-dried wood [12, 13]. Therefore, regression lines at FSP were determined for small specimens of sugi, todomatsu and hinoki to investigate species dependency.

The second issue from our previous work was a lack of generality of the results because the same sugi lumbers were used to measure the moisture contents by drying and from the regression line calculated from their vibrational properties. In addition, from the standpoint of general use of this method, it is preferable to verify whether it is possible to estimate the moisture content of logs, which is the rawest condition of wood. Therefore, in this study, the moisture contents were estimated in green logs that were different from the logs used to prepare small specimens.

Materials and methods

Preparation of small specimens

For small specimens [350 (L) × 17 (R) × 24 (T) mm or 300 − 320 (L) × 15 (R) × 20 (T) mm] of green wood, 59 were prepared from 11 sugi (*Cryptomeria japonica*) logs purchased at a market in Kyoto, 44 were prepared from nine todomatsu (*Abies sachalinensis*) logs collected from the Kitami or Kamikawa regions of Hokkaido Prefecture, and 28 were prepared from four hinoki (*Chamaecyparis obtusa*) logs harvested at the Kyoto University Kamigamo Experimental Station in Kyoto. Average and standard deviation of densities of sugi, todomatsu and hinoki small specimens were 330 (standard deviation (SD) 13), 412 (SD 45), 340 (SD 35) g/cm^3, respectively. The test specimens were prepared from both sapwood and heartwood. To minimize defects in the small specimens, they were prepared so that they did not contain apparent reaction wood, knots larger than 10 mm in diameter, dead knots, or rotten wood. All specimens were confirmed to be above the FSP at the time of preparation and were sealed and seasoned in a plastic bag for at least 1 day at about 20 °C and 50% relative humidity (Rh).

Vibrational test for small specimens

The configuration of the vibration test for small specimens is shown in Fig. 1. Specimens fitted with thin stainless-steel pieces at each end were suspended horizontally by two threads at the nodal points for the primary mode of flexural vibration. The vibration of each specimen was excited

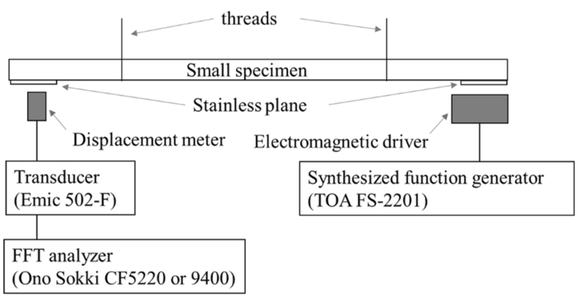

Fig. 1 Configuration of vibration test for small specimens

at frequency increments of 1 Hz by the electromagnetic driver of a synthesized function generator (FS-2201; TOA, Kobe, Japan). Vibration was detected at the other end of the specimen by a displacement meter (502-F; EMIC, Tokyo, Japan) and was recorded through a fast Fourier transform (FFT) analyzer (CF-5220 or CF-9400; Ono Sokki, Yokohama, Japan). The frequency that induced the largest wave amplitude was defined as the resonance frequency. The measured resonance frequencies ranged from 300 to 900 Hz despite previous studies having shown no frequency dependence [19, 20]. Furthermore, the logarithmic decrement of the waveform attenuation at the resonance frequency was calculated after excitation was stopped. Tests were performed at 20 °C and 50% Rh. The weight of each specimen was more than 30 g, whereas the weight of the stainless-steel plate was about 0.08 g, which was considered to be sufficiently small to have no effect on vibration. Weight decrease during the test was less than 0.5%, which allowed the weight to be treated as constant.

In our method for estimating the moisture content, the specific dynamic Young's modulus (E/ρ) and tangent loss ($\tan\delta$) must be known.

Here, E/ρ can be given by:

$$\frac{E}{\rho} = 0.0789 f_r^2 l^4 \frac{A}{I}, \tag{1}$$

where f_r (Hz) is the natural resonance frequency of free–free flexural vibration, and A (mm^2), I (mm^4), and l (mm) are the area of cross section, the area moment of inertia, and the length of the beam, respectively. At the same time, logarithmic decrement λ can be calculated from the attenuation waveform. By using λ, $\tan\delta$ near the resonance frequency can be expressed as:

$$\tan\delta = \frac{\lambda}{\pi}. \tag{2}$$

Correction of vibrational properties of small specimens

In our proposed method, it is necessary to clarify the correlation between E/ρ and $\tan\delta$ at precisely 30% moisture content. However, the moisture contents of small specimens show variation despite being above the FSP. Therefore, it is important to correct these two vibrational properties values to those at 30%. It is known that both E and $\tan\delta$ do not change above the FSP [21, 22]. However, as moisture content increases, E/ρ decreases because ρ becomes larger. Therefore, E/ρ values must be corrected to those at 30%. Let E/ρ at moisture content u be E_u/ρ_u, where u is above 30%. It can be assumed that $E_u = E_{\mathrm{FSP}} = E_{30}$ because E is constant above the FSP. Therefore, E_{30}/ρ_{30} can be calculated from Eq. (3) using the oven-dry density of specimens:

$$\frac{E_{30}}{\rho_{30}} = \frac{100+u}{130}\frac{E_{30}}{\rho_u} = \frac{100+u}{130}\frac{E_u}{\rho_u}. \tag{3}$$

Preparation of log specimens

A total of 58 logs (30 sugi, 23 todomatsu and 5 hinoki) were used as log specimens for moisture content estimation. The sources of logs were the same as those of the logs used for small specimens, but the same logs were not used. All logs retained bark except for 18 todomatsu logs that were debarked. The range of diameter of all logs at the top end was 200–300 mm; each was about 4 m long. Most of the logs were also measured as 3-m specimens by cutting 1 m from the top end after analysis of the 4-m specimen. Log length was measured by convex in units of 5 mm. By assuming the shape of the log cross section was elliptical, both large and small diameters were measured at bottom and end cross section of each log. An average of the four diameters was used as a representative diameter of each log when calculating E/ρ.

Vibrational test of log specimens

The configuration of vibration test for log specimens is shown in Fig. 2. Vibrational tests of logs were conducted outdoors at 10–20 °C and 30–60% Rh at Daiken Co. (Okayama), or at Kitashirakawa or Kamigamo Experimental Station of Kyoto University in Kyoto. Logs were supported at two nodal positions for the primary mode of flexural vibration by extruded polystyrene foam (30 mm thick, 150 mm wide; Dupont Styrofoam) on wooden blocks. In tests of 21 sugi logs, the logs were supported directly on two wooden blocks. A TEAC 701 piezoelectric acceleration sensor (frequency range, 3–30,000 Hz; weight, 3.04 g; TEAC, Tokyo, Japan) was attached to the side of the log near the midpoint (see Fig. 2). Vibration was excited by striking the side of the log near the bottom end with a plastic hammer. A signal from the sensor was amplified threefold using an amplifier (TEAC SA-611), high-pass filtered at 10 Hz or C-weight filtered using a FFT analyzer (Ono Sokki CF5220 or CF9400) to eliminate the low-frequency domain. The logarithmic

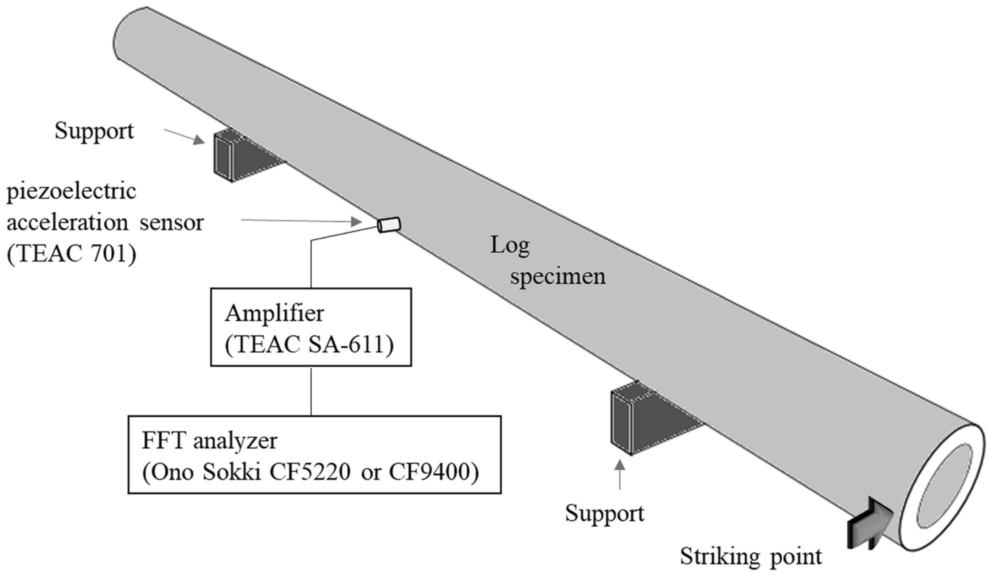

Fig. 2 Configuration of vibration test for log specimens

decrement λ was obtained from the waveform during the first 2 s after impact. The resonance frequency f_r was obtained in 0.5-Hz increments from the frequency spectrum as processed using a Hanning window. The two vibrational properties (E/ρ and $\tan\delta$) were calculated using Eqs. (1) and (2) from averaged values of f_r and λ obtained from at least four measurements. Although the minimum length-to-diameter ratio of all logs was 10.0, the ratios of most of the logs were more than 12.0; the influence of shear deformation was ignored in this study.

Some logs with elliptical cross section had two resonance frequencies in primary mode because both the large and small diameter could act as height when vibrating. In this study, the average of two resonance frequencies was defined as the assumed resonance frequency.

Measurement of moisture contents of log specimens

To measure the moisture content of a log, four disks (each ~ 40 mm thick) were cut from the interior of the log at intervals of 750–1000 mm. The average moisture content of four disks measured by oven-dry method was defined as the measured moisture content of the log.

Moisture content estimation of log specimens

Our proposed method of estimating moisture content requires E/ρ_u, $\tan\delta$ of the target specimen of moisture content u, and the regression line of the correlation between E/ρ_{30} and $\tan\delta$ at 30% moisture content [15]. In this study, the regression lines were calculated from small specimens for sugi, todomatsu and hinoki. The target specimens were 4-m and 3-m specimens from 56 logs, giving a total number of 86 specimens of the three species. Note that in this study, both bound water and free water are supposed to vibrate at the same phase as wood solid [23].

Let Eq. (4) be the regression line of the correlation at 30% moisture content as follows:

$$\log(\tan\delta) = a\log\left(\frac{E}{\rho_{30}}\right) + b, \tag{4}$$

where a (< 0) is the slope and b is the intercept.

The change in this correlation for moisture contents above the FSP is then discussed. The E and $\tan\delta$ values are constant for moisture contents above the FSP [21, 22], whereas the apparent density ρ changes with the moisture content as in Eq. 3. Therefore, substituting Eq. 3 into Eq. 4 yields:

$$\log(\tan\delta) = a\log\left(\frac{E}{\rho_u}\right) + b + a\log\left(\frac{100+u}{130}\right), \tag{5}$$

where u is the moisture content of the target specimen. Figure 3 shows the relationship between Eqs. 4 and 5. If moisture content u gets larger in the range of above 30%, Eq. 5 shifts to the left keeping the same slope. When we have E/ρ_u and $\tan\delta$ of a specimen whose moisture content is unknown, we can find u from the regression line that pass through the point of the specimen. Here, let E/ρ_u and $\tan\delta$ of the target specimen be written as $(E/\rho_u)_t$ and $\tan\delta_t$, respectively. Substituting them into Eq. 5 gives:

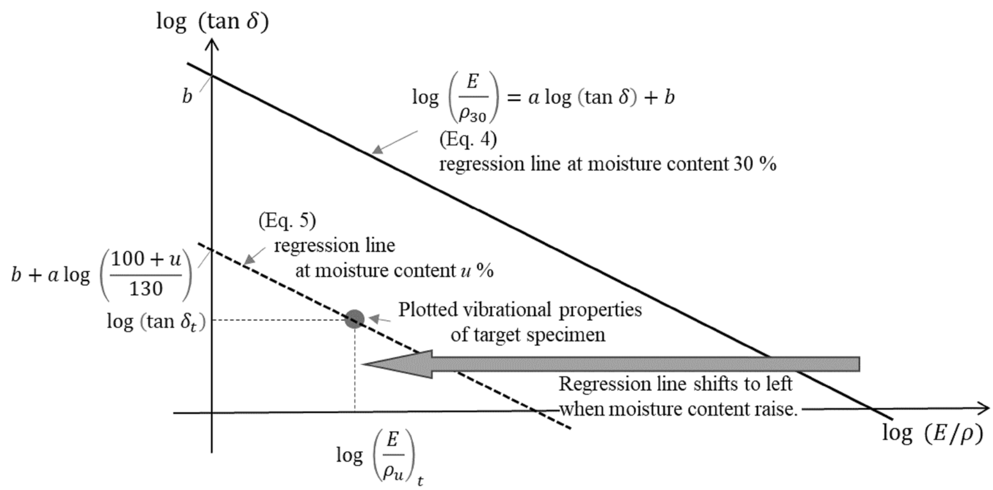

Fig. 3 Change of the regression line of correlation between E/ρ and $\tan\delta$ with changing moisture content

$$\log(\tan\delta_\mathrm{t}) = a\log\left(\frac{E}{\rho_u}\right)_\mathrm{t} + b + a\log\left(\frac{100+u}{130}\right). \tag{6}$$

To find u, Eq. 6 can be rewritten to yield:

$$\log\left(\frac{100+u}{130}\right) = \frac{1}{a}\log(\tan\delta_\mathrm{t}) - \log\left(\frac{E}{\rho_u}\right)_\mathrm{t} - \frac{b}{a},$$

$$u = 130 \times 10^{p\log(\tan\delta_\mathrm{t}) - \log\left(\frac{E}{\rho u}\right)_\mathrm{t} + q} - 100, \tag{7}$$

where $p = \frac{1}{a}$ and $q = -\frac{b}{a}$.

The moisture content u can be obtained via Eq. 7 using E/ρ_u and $\tan\delta$ for a wood specimen of a given species when the a and b values for the wood species are already known.

Results and discussion

Calculation of regression line for each species from small specimens

Figure 4 shows the correlation between E/ρ and $\tan\delta$ at 30% moisture content as calculated from the vibrational properties of green small specimens of sugi, todomatsu and hinoki. For comparison, sapwood and heartwood are plotted separately (Fig. 4). Consistent with previous reports [11–14], there were strong negative correlations between E/ρ and $\tan\delta$. This correlation is thought to be caused by the MFA of the S_2 layer in the cell wall [14]. When MFA decreases, the fiber direction becomes almost consistent with the MFA, leading to larger E/ρ and smaller $\tan\delta$. Conversely, when MFA increases, the influence of the amorphous matrix on mechanical properties gets relatively larger, leading to smaller E/ρ and larger $\tan\delta$. For sugi and todomatsu, no difference was observed in trends between sapwood and heartwood; therefore, each regression line was created by least-squares treatment of data for sapwood and heartwood. For hinoki, some specimens including sapwood were out of correlation to the higher side of $\tan\delta$. The regression line of hinoki should be made both from sapwood and heartwood as same as sugi and todomatsu. However, we could not get proper regression line from both because of small number of specimens and large variation of sapwood from heartwood. Therefore, in this study, the regression line was obtained from only heartwood specimens.

Figure 5 compares the regression lines of sugi, todomatsu and hinoki heartwood. The regression lines of hinoki and sugi were very similar, though that of todomatsu was clearly to the side of larger $\tan\delta$ from that of sugi and hinoki. In addition, the regression for sugi lumber reported in our previous study [15] was consistent with the correlation observed for sugi in this study.

Differences of correlation between this study and previous research

The regression line in this study was compared with those observed in previous studies. In previous research, few studies have investigated the vibration of green wood specimens [24], and there is no report on the correlation of green wood properties. In contrast, many studies [11–14] have investigated air-dried wood and have shown that the slope of the regression line of the correlation of air-dried small specimens ranged between − 0.5 and − 0.7. Moreover, when the moisture content was increased by conditioning, the slope of the regression line changed slightly while the intercept increased [16–18]. Figure 6 compares the regression

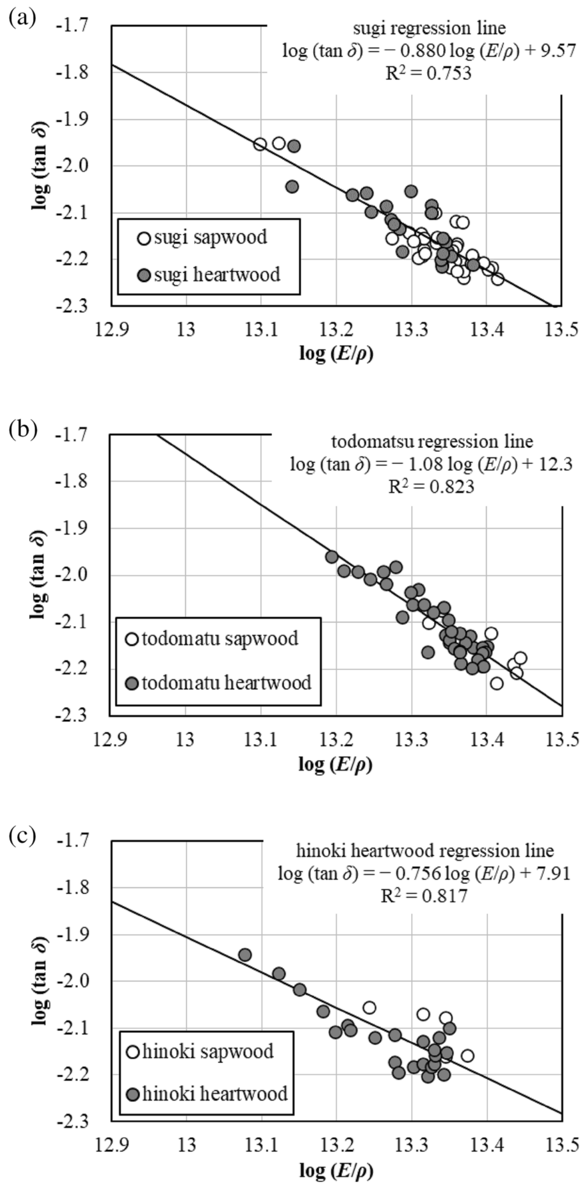

Fig. 4 Relationships between E/ρ and $\tan\delta$ for each species. **a** Sugi, **b** todomatsu, **c** hinoki

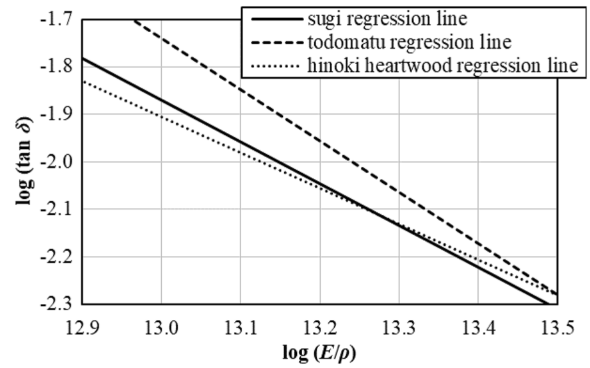

Fig. 5 Comparison of regression lines for correlation between E/ρ and $\tan\delta$ for green specimens of sugi, todomatsu and hinoki heartwood

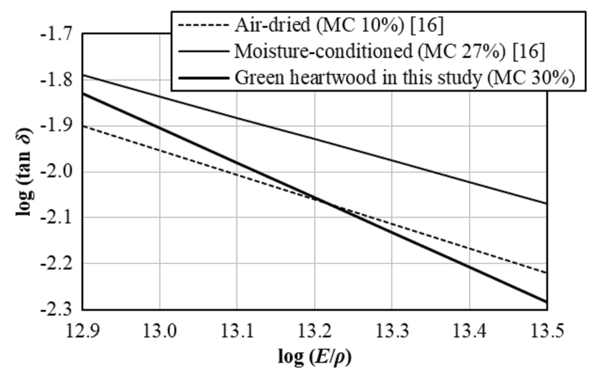

Fig. 6 Comparison of regression lines for correlation between E/ρ and $\tan\delta$ for air-dried hinoki (10% moisture content) and moisture-conditioned hinoki (27%) from previous studies [16] and hinoki green heartwood (30%) in this study

line from this study using green wood with those from previous research [16] for air-dried or moisture-conditioned wood. The regression line at 27% moisture content (previous research) was dissimilar to the line for 30% moisture content from this study. Furuta et al. [25, 26] reported that there are some significant differences in the mechanical properties between green wood and water-swollen wood which was estimated to be caused by strain accumulated in the drying history. From this, it was suggested that the observed difference in regression lines between green wood and moisture-conditioned wood was attributed to the differences of drying history.

Moreover, in this study, regression line of todomatsu is clearly different from those of sugi and hinoki though, according to previous research, the regression lines of air-dried softwoods are almost the same regardless of species except for some species with abundant extractives [27, 28]. Typically, the E/ρ of todomatsu distributes more to the higher side than that of sugi or hinoki both in green wood as in Fig. 4 and in air-dried as in previous researches [29–33]. This is consistent with the previous researches [29–33] that the MFA of todomatsu is smaller than those of sugi and hinoki in both juvenile and mature wood. Therefore, it can be considered that for the same E/ρ, todomatsu is closer to juvenile wood than sugi and hinoki. It is already known that juvenile wood has not only larger MFA, but has different tracheid length and thinner cell walls [33, 34]. These results suggest that the species dependence of the regression line observed only for green wood is due to the fact that the $\tan\delta$ of green wood is affected not only by MFA, but also by other anatomical characteristics.

Results of moisture content estimation of logs

Moisture contents of logs were estimated using the vibrational properties of logs and the regression line of the correlation between E/ρ and $\tan\delta$ at 30% moisture content for each species. However, given that the $\tan\delta$ of 22 sugi logs that were supported by wooden blocks were obviously larger than those for logs supported by polystyrene foam, they were corrected into assumed values of $\tan\delta$ for support by polystyrene foam based on the regression line of the correlation between $\tan\delta$ for support by wooden blocks and support by polystyrene foam as obtained from seven 3-m sugi logs. Equation (8) is the regression line, where $\tan\delta_{PF}$ and $\tan\delta_w$ denote $\tan\delta$ supported by polystyrene foam and wood, respectively. The R^2 value was 0.761. All $\tan\delta$ became smaller by this correction:

$$\tan\delta_{PF} = 0.418\tan\delta_w + 0.00483. \tag{8}$$

Figure 7 shows the results of moisture content estimation for a total of 86 logs: 21 sugi logs with corrected values of $\tan\delta$, 14 sugi logs originally supported by polystyrene foam, 41 todomatsu logs and 10 hinoki logs. The results from 3-m and 4-m logs are shown together. Table 1 shows the average and standard deviation of the difference between measured moisture contents and estimated moisture contents of logs of each species and all logs in Fig. 7 (except the log marked by arrow). From Fig. 7 and Table 1, it was apparent that logs of all three species could be estimated with the similar accuracy by calculating from regression lines peculiar to each species. The data point marked by an arrow in Fig. 7 was from a sugi log that had strong compression wood with pith

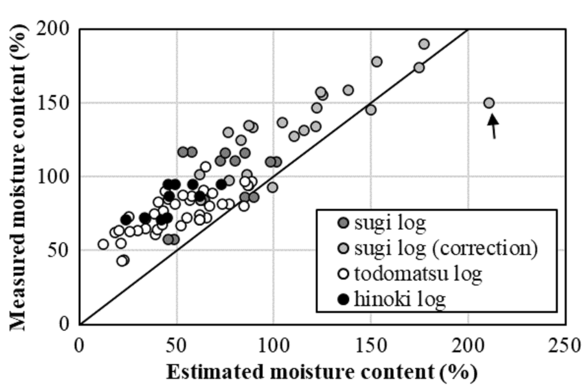

Fig. 7 Relationship between estimated moisture contents and measured moisture contents. Arrow shows data from a log with compression wood

Table 1 Difference between estimated and measured moisture contents in three species

Species	Sugi	Todomatsu	Hinoki	All
Number of logs	34	41	10	85
Average of difference (% in moisture content)	24.0	25.1	36.0	25.9
Standard deviation of difference (% in moisture content)	18.2	13.9	9.92	15.7

eccentricity. Given that compression wood has a different correlation between E/ρ and $\tan\delta$ from that for normal wood [35, 36], the moisture content of the log could not be estimated.

The standard deviation in the estimation of this study (15.7%) is larger than that of our previous study (8.9%), which investigated samples of 50-mm-square sugi lumber. The precision in the previous study was high because the regression line was calculated from sugi lumber specimens for which the moisture content was estimated. Therefore, the standard deviation acquired in this study is considered to be the general degree of precision for the method. This variation is thought to be derived from both measurement error, which include vibrational properties and measured moisture contents, and variation of logs, which include dispersion relative to the regression line, density and moisture content within logs and non-uniform log shapes.

The cause of the 25.9% systematic error was investigated. Regression lines were obtained from small specimens suspended by threads, whereas the vibrational properties of logs were measured on polystyrene foam supports. For different modes of support, it is expected that $\tan\delta$ will vary because the degree of energy dissipation through the supporting objects can change [37, 38]. To investigate the influence of the supporting system on $\tan\delta$, a total of six green sugi logs (100 mm diameter, 1.5–2.2 m long) were used to determine $\tan\delta$ when suspended by ropes or when supported by polystyrene foam. The $\tan\delta$ values for logs supported by polystyrene foam were always higher than the values for logs suspended by ropes, and the ratio of values was 1.17 (SD 0.20). If $\tan\delta$ were to increase by 17%, the estimated moisture content would decrease by 20–40%, which is consistent with the systematic error of the estimation in this study.

Effect of different regression lines in each species on the estimation

Possibility of using same regression line regardless of species is investigated. From Fig. 5, the difference in log (E/ρ)

between sugi and todomatsu regression lines is about 0.1 when log (tan δ) is − 2.0, which is the average of tan δ of 86 logs. Since in our estimating method moisture contents are calculated from the distance from the regression line, if we estimate moisture content of sugi logs using todomatsu regression line, estimated moisture content increases about 50–70% because of the difference in log (E/ρ). Therefore, we cannot regard sugi and todomatsu regression line as the same. On the other hand, because the difference in log (E/ρ) between sugi and hinoki regression lines is small enough to be about 0.02 when log (tan δ) is − 2.0, if we exchange sugi and hinoki regression lines, estimated moisture content change about 10%, which is thought to be within the variation of estimation.

Conclusion

The moisture contents of sugi, todomatsu and hinoki logs (total $n=86$) were estimated using our proposed method of moisture content estimation. This method is based on the dependency of the regression line of the correlation between E/ρ and tan δ on moisture content above the FSP, as suggested in our previous study [15]. First, the regression lines of the correlation at 30% moisture content were obtained from green small specimens of the three species. The regression lines at 30% moisture content in this study were significantly different from those at 27% moisture content for moisture-conditioned small specimens in previous research. Moreover, the regression lines in this study showed species dependency that was not observed for air-dried wood in previous research. These differences between this study and previous research were attributed to the differences in tan δ between green wood and moisture-conditioned wood caused by drying history. The moisture contents of logs (not those used to prepare small specimens) were estimated using the regression lines. As a result, the moisture content was estimated with a standard deviation of 15.7% and a systematic error of 25.9% that was attributed to the different supporting systems used for small specimens and logs. Contributors to the standard deviation were thought to be local variation within the logs and measurement errors incurred in the measurement of vibrational properties and moisture contents.

Abbreviations

FFT	Fast Fourier transform
FSP	Fiber saturation point
MFA	Microfibril angle
Rh	Relative humidity
SD	Standard deviation

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Author contributions
TF contributed to the conceptualization, investigation, methodology, visualization, and original draft of the manuscript. YY contributed to the data curation, formal analysis, investigation, methodology, and review and editing of the manuscript. YF contributed to the conceptualization, data curation, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, and review and editing of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available upon request from the corresponding author.

Declarations

Competing interests
The authors declare that they have no competing interests.

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